Chapter 1. Introduction

1.1 Background to the study

Out of the 4.0 Pg C (1 Pg = 1 Gt = 10^{15} g) recycled to oceans and terrestrial pools from the atmosphere annually, it is estimated that 3.4 Pg of C cycle through the terrestrial sink first before it is recirculated back to the atmosphere (Tans *et al*., 1990; Batjes, 1996). This makes the terrestrial ecosystem a potentially significant sink of or source of atmospheric C. It is postulated that the terrestrial sink has the capacity to sequester the 3.0 Pg C emitted to the atmosphere annually in addition to the C already in the sink (Schimel, 1995; Flach *et al.,* 1997). Consequently, terrestrial ecosystems world-wide are being evaluated for their potential to abate C emissions to the atmosphere. About 75% of the organic carbon (OC) in the terrestrial sink is in the top 1.0 m of soil, 90% of it as soil organic matter (SOM) (Flach, *et al*., 1997) while the rest is distributed between above- and belowground vegetation compartments (Figure 1.1).

Approximately 17 – 50% of soil organic carbon (SOC) is of plant root origin compared with only 7 – 20% from aboveground plant portions (Bolinder *et al*., 1999; Kirsi and Sisko, 1999; Kuzyakov & Domanski, 2000; Coleman *et al*., 2004). Root contributions to SOC are particularly important in deeper horizons where aboveground inputs are of minor importance (Dodd & Mackay, 2011). Plant roots differ in their capacity to explore the soil volume, depending on the geographical location, botanical composition, land-use change and management history, and prevailing environmental factors (Canadell *et al*., 1996; Jackson *et al*., 1996; Casper and Jackson, 1997; Schenk and Jackson, 2002). How these differences might impact on root functional traits associated with foraging for water and nutrients, and cycling of C and in turn mediate the stratification of C stocks down the soil profile is not well understood.

Few studies have investigated the depth distribution of plant roots in relation to profile distribution of SOC stocks (Schulz *et al*., 1996; Jobaggy & Jackson, 2000). Where attempts have been made, fine root biomass (FRB) has been the most used predictor of SOC (Kaisi and Grote, 2007; Garten *et al*., 2011). Little has also been done to explore root traits that could potentially be better predictors of SOC stocks than FRB. For example, it has been reported that increases in specific root length (SRL), fine root volume (FRV), root length density (RLD), root surface area (RSA) and specific root tips abundance (SRTA) can occur without a change in FRB (Ryser & Eek, 2000; Tani *et al*., 2003). This can occur where the same FRB is re-distributed low-order (most distal) branches that have been most positively correlated with large SRL, RSA, FRV and RTA, which are in turn, associated with increased transfer of C to the soil (Guo *et al*., 2008b). For example, Guo *et al*. (2008a) found that the native pasture that had significantly larger soil C stocks than the adjacent pine plantation also had total root length nine times that of the pine in NSW.

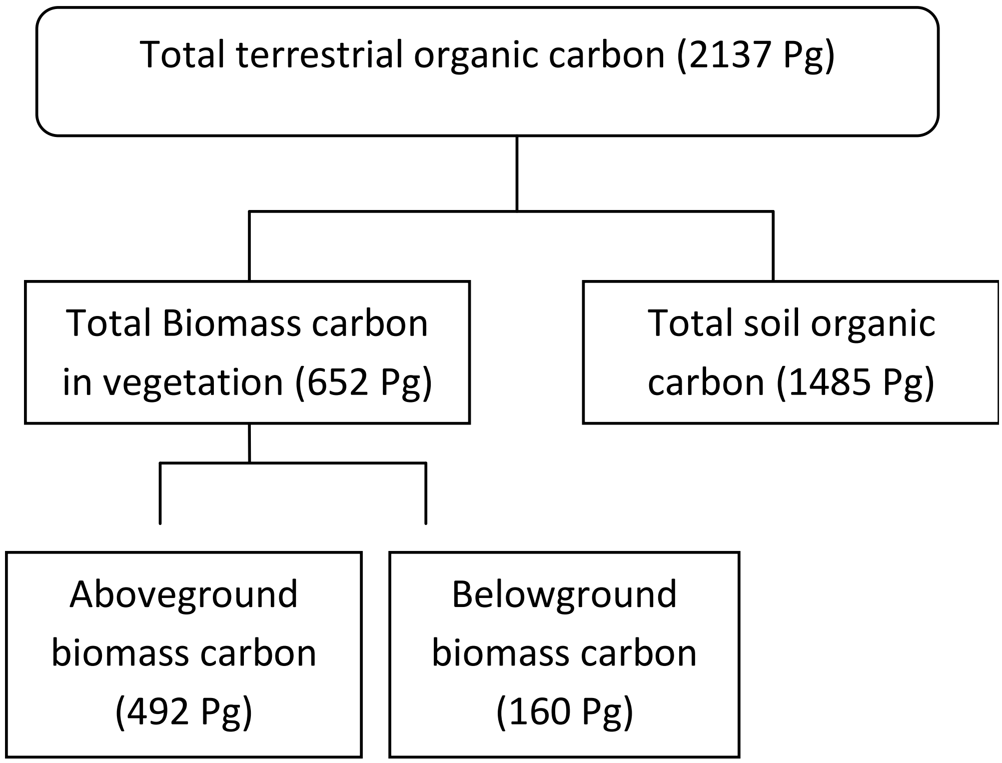

Figure 1.1 The terrestrial carbon sink indicating global estimates of organic carbon stocks (1 Pg = Tg = 10^{15} g). The values are estimates from literature (Schimel, 1995; Batjes, 1996; Flach et al., 1997; Grace et al., 2006).

In addition, roots under the native pasture were longer-lived than those under the pine plantation, suggesting that accumulation of larger soil C stocks under the native pasture was due more to the activity of living roots than through root death and decomposition which were both higher under the pine plantation. More in-depth studies are needed to identify those root morphological traits that are most correlated with soil C stocks and to determine if these correlations are consistent across land-uses, sites and species. These insights can shed light on the specific mechanisms and processes through which fine roots input C to the soil and how these are impacted on by land-use and management.

1.2 Problem statement

Plants differ in their ability to explore the soil solid matrix (Canadell *et al*., 1996; Greenwood and Hutchinson, 1998; Schenk and Jackson, 2002; Arora and Boer, 2003; Lodge and Murphy, 2006). The interplay among land-uses, species and environmental factors in mediating differences in soil exploration patterns and the associated changes in root traits are not well understood. In addition, FRB is the variable that has been used the most to predict soil C stocks (Guo *et al*., 2007; Kaisi and Grote, 2007). However, FRB is not always the best predictor of soil C stocks (Guo *et al*., 2008b) which is predominantly a function of fine roots whose contribution to root biomass is relatively small (Akinnifesi *et al*., 1999; Wang *et al*., 2006; Guo *et al*., 2008b), because of the low tissue density of fine roots (Ryser & Eek, 2000). Furthermore, plant root phenology has been reported to vary with growing season and light intensity (Jacksosn and Caldwell, 1992; Wahl *et al*., 2001; Garten *et al*., 2011), depending on the photosynthetic pathway and level of shade-tolerance of the species (Begna *et al*., 2002). The relative importance of the contributions of these factors to changes in C stocks on the Northern Tablelands of NSW has not been investigated. Although land-use effects and differences among species have been widely reported to influence root litter mineralisation rates (Fu *et al*., 2002; Kuzyokov and Larionova, 2005), empirical studies to back up these claims are few, especially on the Northern Tablelands of NSW. Little is also known about root litter decomposability and the factors influencing it (Personeni & Loiseau, 2004). This information is crucial because root litter decomposability is one of the pathways through which plants input C to the soil (Jones *et al*., 2009) and also influence priming of soil organic matter (de Graaf *et al*., 2010).

1.3 Study justification

Plant roots are increasingly, being reported as a significant source of C in soil especially in deeper layers (Guo *et al*., 2007; Dodd and Mackay, 2011). The morphology and depth distribution of fine roots are important determinants of the survival of plants. It is imperative to identify root functional traits most correlated with SOC stocks and how these are impacted by land-use or vary among species during critical growth stages. Insights into these knowledge gaps will increase our ability to infer changes in the SOC stocks most sensitive to changes in land-use and management and inform modification to existing land-uses to foster C sequestration belowground. In-depth insights into these interrelationships will shed light on (i) root proliferation and spatial exploration patterns of soil, (ii) those root functional traits most associated with accumulation of SOC stocks, and (iii) potential root turnover and rate of transfer of root C to soil.

1.4 Study Objectives

1.4.1 Broad objective

Evaluate root contributions to carbon sequestration in an Alfisol (Chromosol) on the Northern Tablelands of NSW, Australia.

1.4.2 Specific objectives

a. Evaluate the impact of land-use on profile distribution of fine root biomass and associated changes in fine root functional traits under improved pastures, native pastures and woodlands across Kentucky, Newholme and Uralla on the Northern Tablelands of NSW.

b. Characterise the distribution of root and soil carbon and nitrogen stocks down the soil profile to 1.0 m under the selected land-uses across the three sites.

c. Identify root functional traits most strongly correlated with SOC and soil dissolved organic carbon stocks under the three land-uses across the three sites.

d. Compare the decomposability of root litters under improved pastures, native pastures and woodlands and between surface and subsurface root litters.

e. Characterise seasonal distribution of root biomass and associated changes in root functional traits down the soil profile of selected C_3 and C_4 grasses of NSW differing in sun- or shade-adaptability at 0% and 75% shading.

f. Examine the seasonal distribution of root and soil carbon and nitrogen stocks of the selected grasses at the two levels of exposure down the soil profile to 1.0 m.

g. Compare the decomposability of root litters under the three species and between surface and subsurface root litters when incubated in a soil of high nitrogen or low nitrogen.

1.5 Study outline

This study was conducted on the Northern Tablelands of New South Wales (NSW), Australia in two phases. Phase I addressed specific objectives (i) – (iv) and Phase II objectives (v) – (viii). This thesis is organised into eight chapters, with Chapter 1 encompassing the general introduction, background to the study, problem statement, study justification and study objectives. Chapter 2 deals with the impact of land-use on profile distribution of fine root biomass and associated changes in root functional traits under three selected land-uses and explores interrelationships among the root traits. The profile distribution of fine root and soil carbon and nitrogen stocks under the land-uses and the root traits most strongly correlated with SOC and dissolved organic carbon (DOC) stocks are explored in Chapter 3. In Chapter 4, the decomposability of root litters under the three land-use × site combinations and how the CO_2-C effluxes vary between surface and subsurface root litters are examined. Chapter 5 examines the seasonal distribution of fine root biomass and associated changes in root functional traits of three C_3 and C_4 native grasses of NSW differing in sun- or shade-adaptability and explores interrelationships among the root traits down to 1.0 m. The profile distribution of fine root and soil carbon and nitrogen stocks among the grass species and the root traits most strongly correlated with SOC and dissolved organic carbon (DOC) stocks are explored in Chapter 6. In Chapter 7, the decomposability of root litters of the three species in relation to their location in the soil profile is examined in a high-N and low-N soil. Chapter 8 explores the general discussion of the results, conclusions and research imperatives (where possible).

1.6 References

Akinnifesi FK, Kang BT, Ladipo DO. 1999. Structural root form and fine root distribution of some woody species evaluated for agroforestry systems. *Agroforestry Systems* 42: 121–138.

Arora, VK, & Boer GJ. 2003 A representation of variable root distribution in dynamic vegetation models. *Earth Interactions* 7(6): 1–19.

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 47, 151 – 163.

Begna SH, Dwyer LM, Cloutier D, Assemat L, DiTomamaso A, Zhou X, Prithiviraj B, Smith DL. 2002. Decoupling of light intensity effects on the growth and development of C_3 and C_4

weed species through sucrose supplementation. *Journal of Experimental Botany* 53(376): 1935–1940.

Bolinder MA, Angers DA, Giroux M, Laverdere MR (1999) Estimating C inputs retained as soil organic matter from corn (*Zea mays* L.). *Plant and Soil* 215, 85 – 91.

Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulz ED (1996) Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108, 583 – 595.

Casper BB, RB Jackson (1997) Plant competition underground. *Annual Review of Ecology and Systematics* 28, 545 – 570.

Coleman DC, Crossley DA, Hendrix PF (2004) Fundamentals of soil ecology. Elsevier, San Diego Academic Press (2nd Edition).

De Graaf, M-A., Classen, A. T., Castro, H. F., Schadt, C. W., 2010. Labile soil carbon inputs mediate the soil microbial community composition and plant residue decomposition rates. New Phytologist 188, 1055–1064.

Dodd, M. B., Mackay, A. D., 2011. Effects of contrasting soil fertility on root mass, root growth, root decomposition and soil carbon under a New Zealand perennial ryegrass/whit clover pasture. Plant and Soil 349(1-2), 291–302.

Flach KW, Barnwell TO Jr, Crosson P (1997) Impact of Agriculture on atmospheric carbon dioxide. In: Soil organic matter in temperate agroecosystems: Long-term experiments in North America (eds Paul EA, Paustian K, Elliot ET, Cole VC), pp. 3–13. CRC Press, Boca Raton, FL.

Fu, S., Cheng, W., Susfalk, R., 2002. Rhizosphere respiration varies with plant species and phenology: a greenhouse pot experiment. Plant and Soil 239, 133 – 140.

Garten CT, Brice DJ, Castro HF, Graham RL, Mayes MA, Philips JR, Post III WM, Schadt CW, Wullschleger SD, Tyler DD, Jardine PM, Jastraw JD, Matamala R, Miller RM, Moran KK, Vugteveen TW, Izaurralde RC, Thomson AM, West TO, Amonette JE, Bailey VL, MettingFB, Smith JL (2011) Response of “Almo” switchgrass tissue chemistry and biomass to N fertilisation in west Tennessee, USA. *Agriculture, Ecosystems and Environment* 140, 289 – 297.

Grace PR, Colunga-Garcia M, Gage SH, Robertson GP, Safir GR (2006) The potential impact of agricultural management and climate change on soil organic carbon of the North Central Region of the United States. *Ecosystems*, 9, 816 – 827.

Greenwood KL, Hutchinson KJ (1998) Root characteristics of temperate pasture in New South Wales after grazing at three stocking rates for 30 years. *Grass and Forage Science* 53, 120 – 128.

Guo LB, Wang M, Gifford RM (2007) The change of soil carbon stocks and fine root dynamics after landuse change from a native pasture to a pine plantation. *Plant and Soil* 299, 251 – 262.

Guo LB, Cowie AL, Montagu KD *et al*. (2008a) Carbon and nitrogen stocks in a native pasture and adjacent 16-year-old *Pinus radiata* D. Don plantation in Australia. Agriculture Ecosystems & Environment 124 (3-4), 205-218.

Guo D, Li H, Mitchell RJ, Han W, Hendricks JJ, Fahey TJ, Hendrick RL (2008b) Fine root heterogeneity by branch order: exploring the discrepancy in root turnover estimates between minirhizotron and carbon isotopic methods. New Phytologist, 177 443–456.

Jackson RB, Caldwell MM. 1992. Shading and the capture of localised soil nutrients: nutrient contents, carbohydrates, and root uptake kinetics of a perennial tussock grass. *Oecologia* 91: 457–462.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. & Schulze, E.D. (1996) A global analysis of root distribution for terrestrial biomes. *Oecologia*, 108, 389 – 411.

Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10(2), 423 – 436.

Kaisi MM, Grote JB (2007) Cropping Systems Effects on Improving Soil Carbon Stocks of Exposed Subsoil, *Soil Science Society of America Journal*, 71(4), 1381 -1388.

Kirsi M, Helja-Sisko H (1999) Assessing fine-root biomass and production in a Scotish pine stand-comparison of soil core and root in-growth core methods. *Plant and Soil*, 201, 43 – 50.

Kuzyakov Y, Domanski G (2000) Carbon input by plants into the soil. *Soil Science* 163, 421 – 431.

Kuzyakov, Y., Larionova, A. A., 2005. Root and rhizomicrobial respiration: a review of approaches to estimate respiration by autotrophic and heterotrophic organisms in soil. Journal of Plant Nutrition and Soil Science 168, 503 – 520.

Lodge GM, Murphy SR (2006) Root depth of native and sown perennial grass-based pastures, North-West Slopes, New South Wales. I. Estimates from cores and effects of grazing treatments. *Australian Journal of Experimental Agriculture* 46, 337 – 345.

Personeni, E., Loiseau, P., 2004. How does the nature of living roots affect the residence time of carbon in the root litter continuum? Plant and Soil 267, 129–141.

Ryser P, Eek L (2000) Consequences of phenotypic plasticity vs inter-specific differences in leaf and root traits for acquisition of aboveground and belowground resources. *American Journal of Botany* 87, 402 – 411.

Schenk HJ, Jackson RB (2002) Rooting depths, lateral root spreads and belowground / aboveground. Allometries of plants in water-limited ecosystems. *Journal of Ecology*, 90, 480 – 494.

Schimel DS (1995) Terrestrial ecosystems and the carbon cycle. *Global Change Biology*, 1, 77 – 91.

Schultz ED, Mooney HA, Sala OE, Jobbagy E, Buchmann N, Bauer G, Canadell J, Jackson RB, Loreti J, Oesterheld M, Ehleringer JR (1996) Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia. *Oecologia 108: 389 – 411*.

Smith P (2008) Land use change and soil organic carbon dynamics. *Nutrient Cycling in Agroecosystems*, 81, 169 – 178.

Tani T, Kudo H, Kachi N (2003) Responses of root length/leaf area ratio and specific root length of an understorey herb, *Pteridophyllum racemosum*, to increase in irradiance. *Plant and Soil*, 255, 227 – 237.

Tans PP, Fung IY, Takahashi T. 1990. Observational constraints on the global atmospheric CO_2 budget. *Science* 247(4949): 1431 – 1438.

Wahl S, Ryser P, Edwards PJ. 2001. Phenotypic plasticity of root anatomy in response to light intensity and nutrient supply. *Annals of Botany* 88: 1071–1078.

Wang, H., Inukai, Y. & Yamauchi, A. (2006) Root development and nutrient uptake. *Critical Review Plant Science*, 25, 279 – 301.